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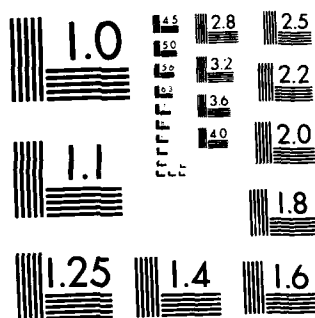UNCLASSIFIED   K S GAGE ET AL. 23 MAR 88 AFOSR-TR-88-0442 F/G 4/1   NL

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In recent years much progress has been made in determining the spectrum of mesoscale atmospheric motions. The frequency spectra of vertical and horizontal velocities have been determined in the free atmosphere by means of the nearly continuous measurement of radial velocity by wind-profiling Doppler radar (Balsley and Carter, 1982; Gage and Nastrom, 1985; Ecklund et al., 1986). In addition, wind measurements by commerical aircraft collected during the NASA Global Atmospheric Sampling Program (GASP) have been analyzed to yeild wavenumber spectra in the upper tropophere and lower atmosphere that cover scales ranging from a few km to 10,000 km (Nastron and Gage, 1985).

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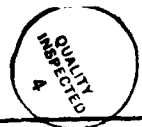
FURTHER DISCUSSION OF THE DYNAMICAL PROCESSES THAT CONTRIBUTE TO THE
SPECTRUM OF MESOSCALE ATMOSPHERIC MOTIONS

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1. INTRODUCTION

In recent years much progress has been made in determining the spectrum of mesoscale atmospheric motions. The frequency spectra of vertical and horizontal velocities have been determined in the free atmosphere by means of the nearly continuous measurement of radial velocity by wind-profiling Doppler radar (Balsley and Carter, 1982; Gage and Nastrom, 1985; Ecklund et al., 1986). In addition, wind measurements by commercial aircraft collected during the NASA Global Atmospheric Sampling Program (GASP) have been analyzed to yield wavenumber spectra in the upper troposphere and lower stratosphere that cover scales ranging from a few km to 10,000 km (Nastrom and Gage, 1985).

The synthesis of the observed atmospheric spectra into a dynamical framework has proceeded along several lines. Two conceptual models have been proposed to explain the nature of the spectra. The first is analogous to the Garrett-Munk spectrum of internal waves in the ocean. The second relies on a combination of the internal wave spectrum and a spectrum of quasi-horizontal motions presumably associated with the vorticity bearing mode of fluid motions. This vortical mode possesses vertical variation and is often referred to as quasi-two-dimensional or stratified turbulence. In the following sections we shall briefly review the current status of these two competing models of mesoscale atmospheric spectra and present some new results of an analysis of the frequency dependence of frequency spectra of horizontal velocity upon background wind speed that may provide a basis for evaluating the relative contributions of waves and turbulence to the spectrum of horizontal motions in the atmosphere.

2. BACKGROUND

The idea that the spectrum of mesoscale atmospheric motions might be due to an incoherent spectrum of internal wave motions analogous to the Garrett-Munk spectrum in the ocean appears to have originated with the work of Dewan (1979) and VanZandt (1982). VanZandt examined the observed atmospheric spectra of horizontal motions and showed that it was possible to construct a universal model of the atmospheric spectrum in the spirit of Garrett-Munk that fit the atmospheric observations quite well. However, since little information was available at the time on the

magnitude and shape of the spectrum of atmospheric vertical motions, the VanZandt model did not take them into account. Subsequently, as summarized in Ecklund et al. (1986), it now appears that a rather flat, nearly universal spectrum of vertical velocity exists in the atmosphere at least under light wind conditions. The possibility that this vertical velocity spectrum is nearly universal has been reinforced by recent results of the Flatland radar (Green et al., 1988) that show that in the absence of significant orography flat vertical velocity frequency spectra are obtained under a wide range of atmospheric conditions. However, the magnitude of this observed vertical velocity spectrum is not consistent with the VanZandt (1982) model spectrum as was pointed out by Gage and Nastrom (1985).

The original VanZandt model spectrum was normalized to fit the observed atmospheric horizontal velocity spectrum. If the observed vertical velocity spectrum is assumed to be an internal wave spectrum, it is possible to calculate the horizontal velocity spectrum of internal waves by employing the polarization relations and dispersion relation for internal waves. The spectrum of horizontal motions due to internal waves using this approach is shown in Fig. 1. Also shown in Fig. 1 are observed horizontal velocity spectra. In these examples, the observed horizontal velocity spectra contain more energy than the model spectrum at all frequencies. While this suggests that other processes besides internal waves may be responsible for the spectrum of horizontal motions, it must be kept in mind that up to this point no attempt has been made to account for Doppler shifting effects. Recently Scheffler and Liu (1986) and Fritts and VanZandt (1987) have been able to model the influence of mean wind speeds on internal wave spectra and their results show that the effect of Doppler shifting on atmospheric internal waves is not negligible.

The possibility that the observed atmospheric spectrum of horizontal motions may be dominated by processes other than internal waves was considered by Lilly (1983) and Gage and Nastrom (1985a, 1985b). These authors suggested that the horizontal velocity spectrum may be a manifestation of the vortical mode of fluid motions also known as stratified turbulence or quasi-two-dimensional turbulence. Lilly based his analysis on earlier work by Riley et al. (1981) that showed that at low Froude numbers it was possible through a scaling analysis to separate the equations of motion into
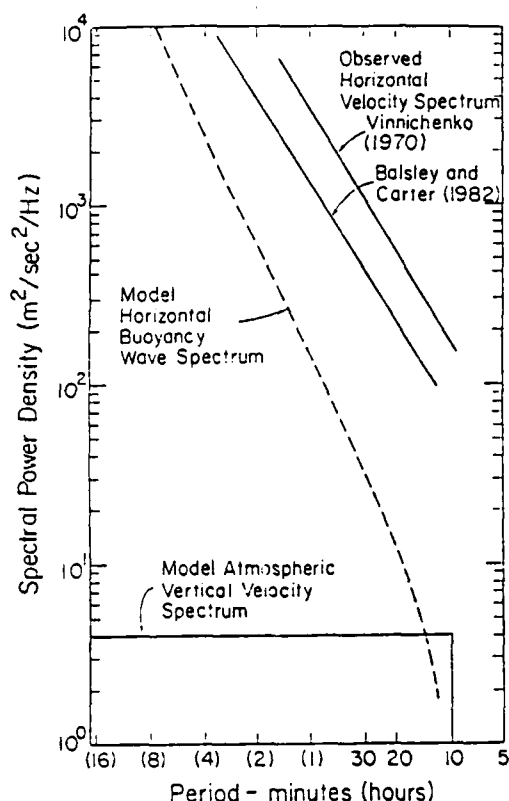
Fig. 1. Comparison of observed frequency spectra of horizontal motions with the frequency spectrum of horizontal buoyancy wave motions consistent with a model tropospheric vertical velocity spectrum.

a set of equations governing wave motions and another set of equations governing turbulence. Physically, at low Froude number in a stratified fluid it should be possible to decompose the motion field into waves and stratified turbulence. The possibility that the observed atmospheric velocity spectra contain contributions from waves and quasi-two-dimensional stratified turbulence has been considered by Gage and Nastrom (1985a, 1985b).

Both points of view discussed above accept the idea that the spectrum of vertical motions is largely determined by a spectrum of internal waves. Only in the importance attached to quasi-two-dimensional turbulence do the points of view differ. Doppler shifting effects may provide a way to differentiate waves and turbulence. The calculations of Scheffler and Liu (1986) and Fritts and VanZandt (1987) provide a means to quantify the Doppler shifting effect of a mean velocity on a spectrum of internal waves. The Taylor-transformation can be used to relate frequency spectra of turbulence to the wave number spectra of atmospheric motions

3.   THE EFFECT OF A MEAN WIND ON INTERNAL WAVE AND TURBULENCE SPECTRA

According to the analysis of Scheffler and Liu (1986) and Fritts and VanZandt (1987) the influence of a mean wind on the spectrum of internal waves can be parameterized by the quantity

$$\beta = \frac{\overline{U} m_*}{N} \qquad (1)$$

where m_* is a characteristic vertical wavenumber, $\overline{U}$ is the mean wind speed, and N is the Brunt-Vaisala frequency. The influence of the mean wind on the spectrum of horizontal velocity for internal waves is illustrated in Fig. 2 which is taken from Fritts and VanZandt (1987). Figure 2 shows that qualitatively the influence of the mean wind is to increase the spectral amplitude at the high frequency end of the spectrum and to decrease the spectral amplitude at the low frequency end of the spectrum. The net effect of the mean wind is to increase (make less negative) the spectral slope above – 2 which is the slope of the model spectrum without Doppler shifting. Note that this change in spectral slope is in the sense required to fit the observed spectral slope in Fig. 1. Note also that only those waves with a component of their phase velocity in the direction of the mean wind are Doppler shifted.
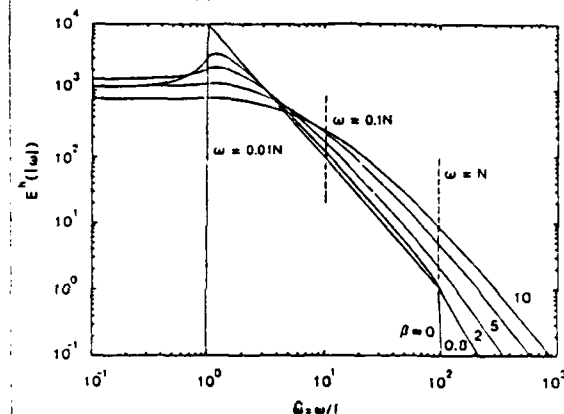

Fig. 2. Doppler shifting effect of a mean wind on a model buoyancy wave spectrum of horizontal velocity. (After Fritts and VanZandt, 1987.)

The Taylor transformation can be used to determine the frequency spectrum of turbulence seen by a fixed observer when a known wavenumber spectrum is advected past at a given velocity. The frequency spectrum is given by

$$E(f) = 2\pi \, E(k)/\overline{U} \qquad (2)$$

where

$$f = \overline{U}k/2\pi \qquad (3)$$

To determine the dependence of the wind speed, we adopt the model wavenumber spectrum contained in Fig. 3. This model wavenumber spectrum is a good approximation to the climatological GASP spectrum (Nastrom and Gage, 1985). Using Eqs. (2) and (3) we calculate the frequency spectra pertinent to various advection velocities as illustrated in Fig. 4. Note that unlike the wave spectra in Fig. 2, the turbulence spectra in Fig. 4 retain their original spectral slope. Their spectral magnitude increases uniformly at all frequencies with increasing advection velocity. Actually, over mountainous terrain, the GASP spectra are modified somewhat (Nastrom et al., 1987) and these modifications should be taken into account in a more complete analysis.
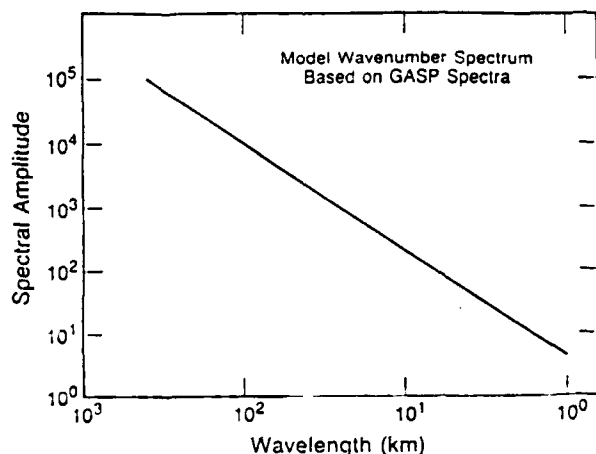
Model Wavenumber Spectrum Based on GASP Spectra

Spectral Amplitude vs Wavelength (km)

Fig. 3. Model horizontal wavenumber spectrum of horizontal velocity based on GASP spectra.

Frequency Spectrum

o 3 ms^{-1}
△ 7 ms^{-1}
+ 13 ms^{-1}
x 20 ms^{-1}
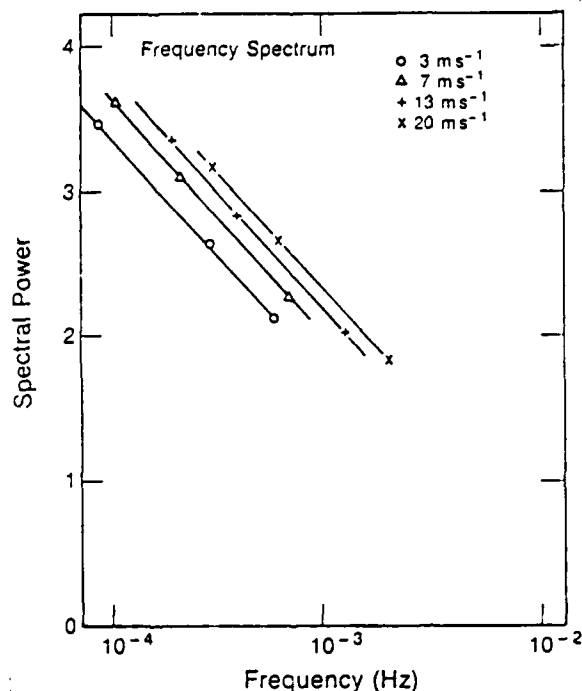
Spectral Power vs Frequency (Hz)

Fig. 4. Doppler shifted frequency spectra of horizontal velocity determined by Taylor transformation of the model wavenumber spectrum contained in Fig. 3.

4. THE OBSERVED DEPENDENCE OF THE FREQUENCY SPECTRUM OF HORIZONTAL VELOCITY UPON WIND SPEED AT PLATTEVILLE, COLORADO

The 50 MHz Doppler radar located at Platteville, Colorado, has been observing horizontal and vertical velocities routinely since 1981. For the purposes of the present paper accumulated data from 1981-1984 were analyzed to determine the dependence of the frequency spectra upon background wind speed. The frequency spectrum of the observed winds were calculated for 3 hour and 9 hour periods and data were stratified according to mean horizontal wind speed. Composite spectra

were formed for each wind speed interval. Composite 3-hour spectra for the zonal wind are shown in Fig. 5. These spectra show a general increase in spectral amplitude with increasing wind speed. Spectral shape does not appear to be greatly affected by increasing mean winds over the range 2 to 20 ms^{-1}.

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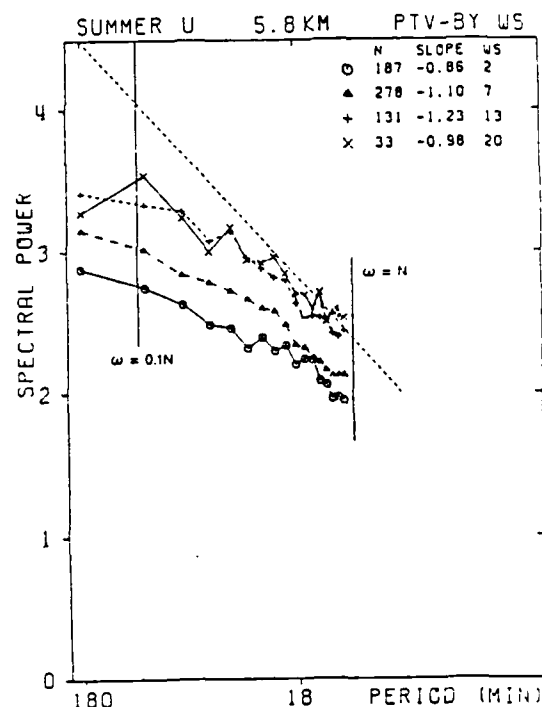|	N	SLOPE	WS
o	187	-0.86	2
▲	278	-1.10	7
+	131	-1.23	13
x	33	-0.98	20

$\omega = N$
$\omega = 0.1N$

SPECTRAL POWER vs PERIOD (MIN)

Fig. 5. Observed 3-hour frequency spectra of horizontal zonal velocity at Platteville, Colorado during summer months stratified by wind speed.

5. COMPARISON OF THE OBSERVED DEPENDENCE OF THE HORIZONTAL VELOCITY SPECTRUM ON MEAN VELOCITY WITH THE WAVE AND TURBULENCE MODELS

In this section we compare quantitatively the dependence of the observed frequency spectrum of horizontal velocity upon mean wind speed with the Doppler shifting effect discussed in Section 3. This is accomplished by determining the change in spectral amplitude with changing wind speed. Since we are concerned primarily with the relative magnitudes of the spectra, all changes in spectral amplitude are determined relative to the spectral amplitude of the non-Doppler shifted (or lowest wind speed) spectrum. Changes in the spectral amplitude are determined as a function of wind speed at several frequencies. The frequencies chosen for the comparison are the Brunt-Vaisala frequency N, a frequency equal to .1N, and a frequency equal to .01N. The observed frequency spectrum does not extend to low enough frequencies to compare with the wave and turbulence models at .01N but the changes in spectral amplitude for the models have been included here for completeness

In order to determine the changes in spectral amplitude for the wave model it is necessary to assign a value to the characteristic

wavenumber m_*. We have for this purpose adopted
a value of $m_* = .75 \times 10^{-3}$ cpm which is consistent
with values anticipated by Fritts and VanZandt
(1987). For the troposphere pertinent to the
summertime Platteville spectra contained in Fig. 5,
we adopt $N = 1.67 \times 10^{-3}$ cps. With these choices
for m_* and N, $\beta = .45\overline{U}$.

       The results of the comparisons are con-
tained in Fig. 6. Altogether there are six curves
plotted in Fig. 6. Each curve gives the spectral
density ratio as a function of wind speed. Curves
with positive (negative) slope have increasing
(decreasing) spectral amplitude with increasing
wind speed. Two curves are plotted for the
observed change in spectral amplitude correspond-
ing to frequencies of N and .1N, respectively.
These curves show a modest _increase_ in slope with
decreasing frequency. The turbulence model result
does not depend on frequency so that only a single
curve is drawn. This curve has a positive slope
intermediate to the slopes of the two curves for
the observed spectra. Three curves are plotted
for the wave model. These curves show the depen-
dence upon wind speed of the model wave spectrum
for frequencies of N, .1N, and .01N, respectively.
The slopes for the three curves _decrease_ rather
markedly with decreasing frequency. This is the
opposite sense of the more modest change noted
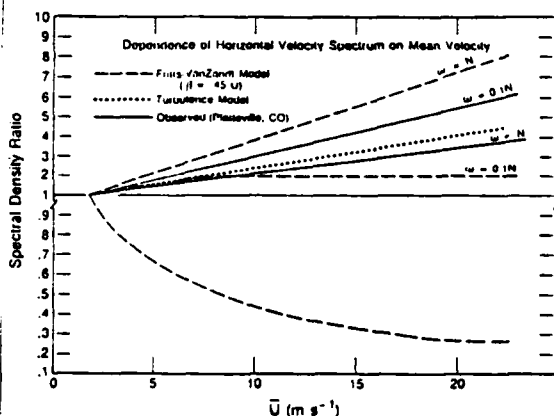previously for the observed spectra.

Fig. 6. Comparison of the observed dependence of
the horizontal velocity spectrum on wind speed
with wave and turbulence models.

6.   CONCLUDING REMARKS

       In this paper we have considered the
dynamical processes that may be responsible for
the observed mesoscale atmospheric wind spectra.
We have addressed the issue of whether the observ-
ed spectrum of horizontal velocity is due primar-
ily to waves or turbulence, by comparing the
dependence of the observed horizontal velocity
spectra on wind speed with the Doppler shifting
effect anticipated for a model wave spectrum and
for a model turbulence spectrum. The results
show that the observed spectra do not follow
either the turbulence model or the wave model
very closely. However, the turbulence model seems
to fit the observations more closely than does
the wave model. (reprints)

The wave and turbulence models employed
here must be considered as approximate and the
results shown are necessarily of a statistical
nature. The observations are limited to a single
location and may not be typical of other locations.
For these reasons the results presented here must
be regarded as preliminary.

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